Multicenter solutions, quivers and their implication for black hole physics

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with

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erc FQXi JOHN TEMPLETON FOUNDATION Agence Nationale de la Recherche ANR DE LA RECHERCHE À L'INDUSTRIE cea SACLAY

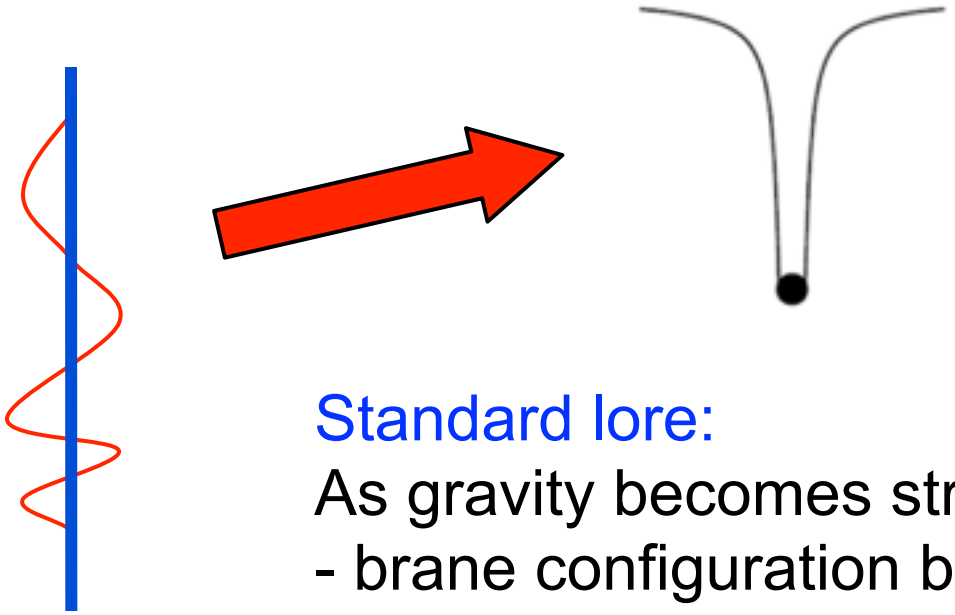
Strominger and Vafa (1996):

Count Black Hole Microstates (branes + strings)

Correctly match B.H. entropy !!!

Zero Gravity

One Particular Microstate at Finite Gravity:



Standard lore:

As gravity becomes stronger,

- brane configuration becomes smaller
- horizon develops and engulfs it
- recover standard black hole

Susskind

Horowitz, Polchinski

Damour, Veneziano

Strominger and Vafa (1996):

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Zero Gravity

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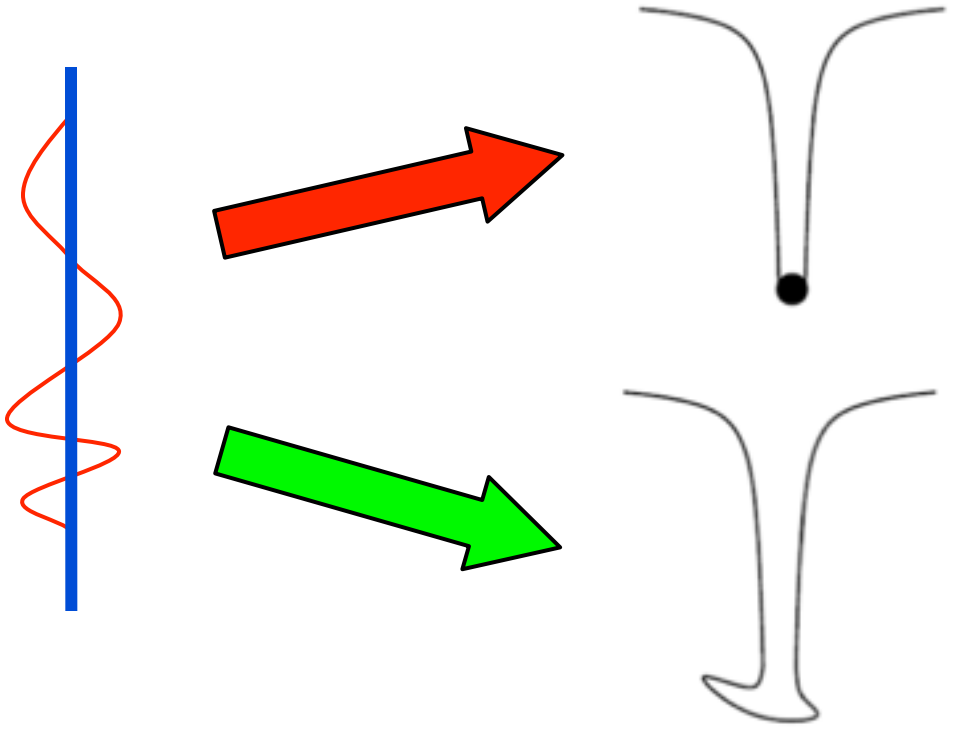


Identical to black hole far away.

Horizon → Smooth cap

Giusto, Mathur, Saxena

Bena, Warner

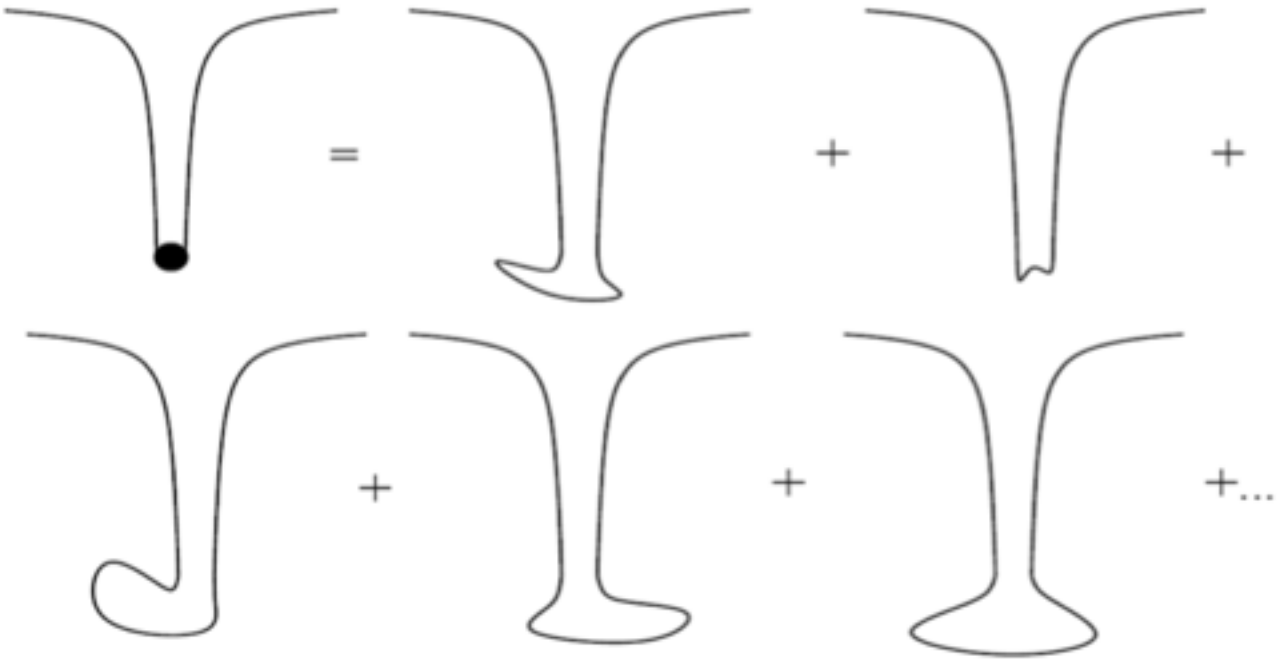
Berglund, Gimon, Levi

BIG QUESTION: Are ***all*** black hole microstates becoming geometries with no horizon ?

?

Black hole = ensemble of horizonless microstate configurations

Mathur 2003



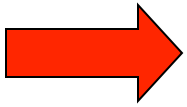
Analogy with ideal gas

Thermodynamics

(Air = ideal gas)

$P V = n R T$

$dE = T dS + P dV$



Statistical Physics

(Air -- molecules)

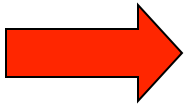
e^S microstates

typical

atypical

Thermodynamics

Black Hole Solution



Statistical Physics

Microstate geometries

Long distance physics

Gravitational lensing

Physics at horizon

Information loss

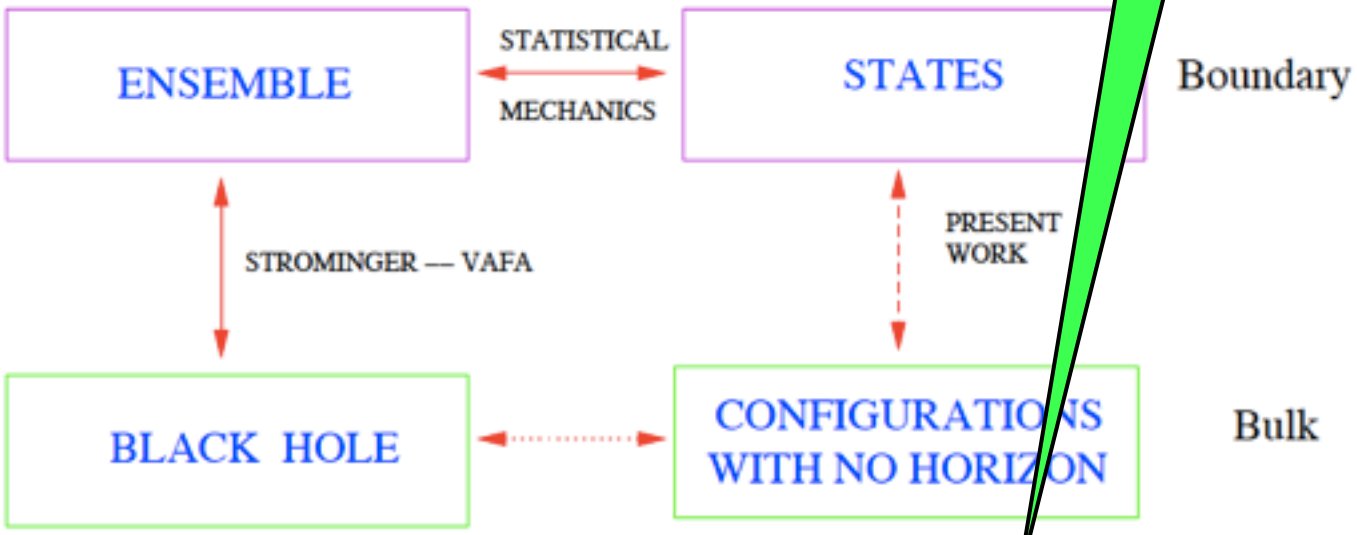
Other formulations:

e.g. Bena, Warner, 2007

- **Thermodynamics (EFT)** breaks down at horizon. New low-mass d.o.f. kick in.

- No spacetime inside black holes. **Quan superposition** of microstate geometries.

Highly Unusual in this field ☺



Not some hand-waving idea - can be established by serious calculations in String Theory

Word of caution

- To replace classical BH by BH-sized object
  - Gravastar
  - Infinite density firewall hovering above horizon
  - LQG configuration
  - Quark-star, you name it …
  - satisfy 2 very stringent tests: Horowitz

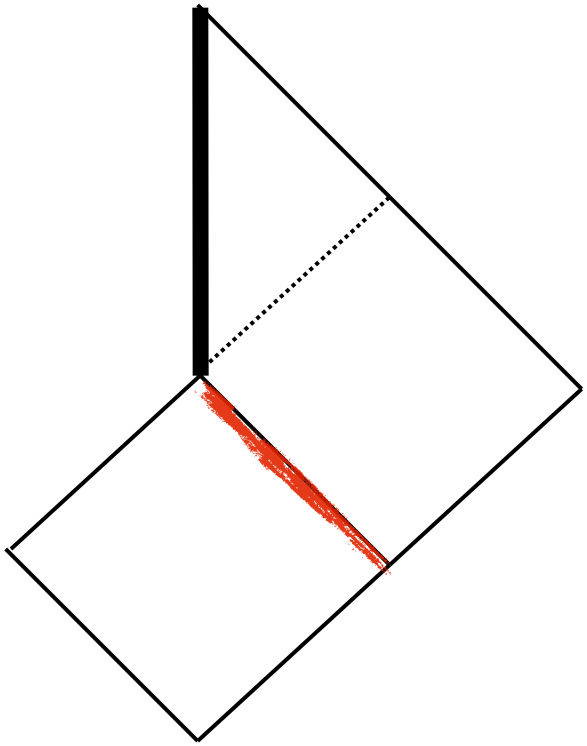
1. Same growth with G_N !!!

- BH size grows with G_N
- Size of objects in other theories becomes smaller

- Multicenter solutions/microstate geometries pass this test
- Highly nontrivial mechanism (responsible for wall-crossing):
- D-brane tension ~ $1/g_s$ ➔ lighter and fluffier as G_N increases

2. Mechanism not to fall into BH

Very difficult !!!



Dogma:

Thou shalt not put anything at the horizon !!!

- Horizon is null
- Must go at speed of light.
- If massive: ∞ boost → ∞ energy
- If massless: dilutes with time (unless extremal)

- Nothing can live there !
  (nor carry degrees of freedom)
- No membrane, no smokescreen
- No (fire)wall, no wave sent by Bob

Must have a support mechanism !

Microstate geometries

M2	0	1	2					
M2	0			3	4			
M2	0					5	6	

3-charge 5D black hole Strominger, Vafa; BMPV

$$S_{BMPV} = 2\pi\sqrt{N_1 N_5 N_P - J^2}$$

$$ds^2 = Z_1^{-2/3} Z_2^{-2/3} Z_3^{-2/3} (dt + \vec{k})^2 + Z_1^{1/3} Z_2^{1/3} Z_3^{1/3} dx^2_{\mathbb{R}^4} + ds^2_{T^6}$$

$$F_{120i} = \partial_i Z_1^{-1} \qquad F_{340i} = \partial_i Z_2^{-1} \qquad F_{560i} = \partial_i Z_3^{-1} \qquad \text{electric}$$

Want solutions with same asymptotics, but no horizon

Microstate geometries

M2	0	1	2						
M2	0			3	4				
M2	0					5	6		
M5	0			3	4	5	6		θ
M5	0	1	2			5	6		θ
M5	0	1	2	3	4				θ

CLOSED CURVE

$\mathbb{T}^6$ $\mathbb{R}^4$

$$ds^2 = Z_1^{-2/3} Z_2^{-2/3} Z_3^{-2/3} (dt + \vec{k})^2 + Z_1^{1/3} Z_2^{1/3} Z_3^{1/3} dx^2_{\mathbb{R}^4} + ds^2_{T^6}$$

$$F_{120i} = \partial_i Z_1^{-1} \qquad F_{340i} = \partial_i Z_2^{-1} \qquad F_{560i} = \partial_i Z_3^{-1} \qquad \text{electric}$$

$$F_{12ij} = G^1_{ij} \qquad F_{56ij} = G^2_{ij} \qquad F_{56ij} = G^3_{ij} \qquad \text{magnetic}$$

Solution depends on G^1 G^2 G^3 Z_1 Z_2 Z_3 $\vec{k}$

Bena, Warner
Gutowski, Reall

BPS Microstates geometries - 11D SUGRA / T^6

5D 3-charge BH (Strominger-Vafa)

Linear system
4 layers:

Bena, Warner
Gutowski, Reall

$\mathbb{R}^4$ base (4D Hyper Kahler)

$$*G^I = G^I$$

$$d * dZ_1 = G^2 \wedge G^3$$

$$d\vec{k} + *d\vec{k} = G^1 Z_1 + G^2 Z_2 + G^3 Z_3$$

Focus on Gibbons-Hawking (Taub-NUT) base:

$$ds^2 = V\left(dx_1^2 + dx_2^2 + dx_3^2\right) + V^{-1}(d\psi + \vec{A})^2$$

$$\nabla \times \vec{A} = \nabla V$$

$V = \frac{1}{r}$ $\mathbb{R}^4$

$V = 1 + \frac{1}{r}$ Taub-NUT

8 harmonic functions

Gauntlett, Gutowski,
Bena, Kraus, Warner

BPS Black Rings (in Taub-NUT)

Elvang, Emparan, Mateos, Reall; Bena, Kraus, Warner; Gaiotto, Strominger, Yin

$$S = \pi \sqrt{2n_1 n_2 \bar{N}_1 \bar{N}_2 + 2n_1 n_3 \bar{N}_1 \bar{N}_3 + 2n_2 n_3 \bar{N}_2 \bar{N}_3 - n_1^2 \bar{N}_1^2 - n_2^2 \bar{N}_2^2 - n_3^2 \bar{N}_3^2 - 4 n_1 n_2 n_3 J_T}$$

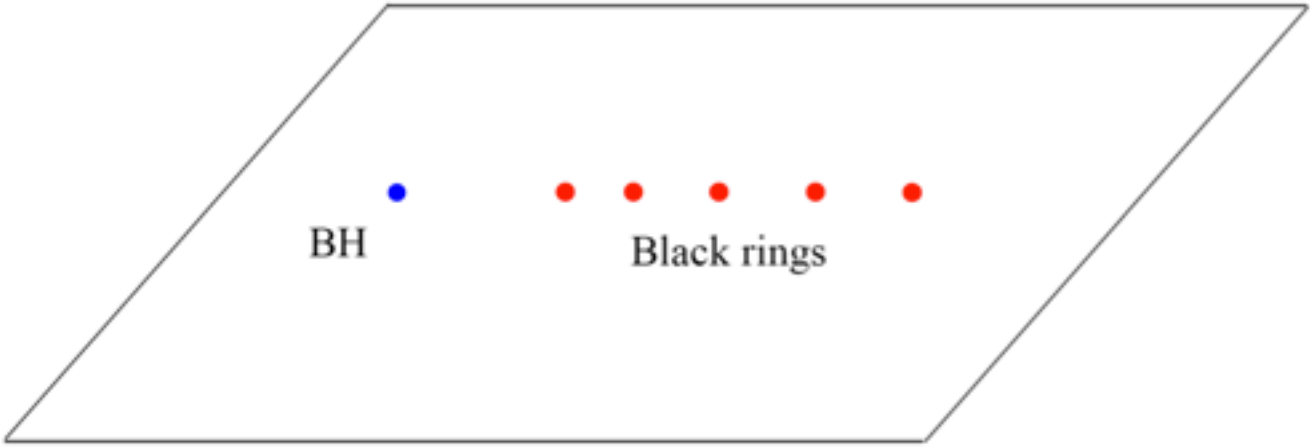
4D BH: D2 charges $\bar{N}_1\ \bar{N}_2\ \bar{N}_3$, D4 charges $n_1\ n_2\ n_3$ and D0 charge J_T

- Position of ring = F(charges, moduli); grows with g_s
- Ring can go to infinity and disappear from spectrum
- Wall crossing - the 5D version

Examples: Multiple Black Rings

- 5D BH on tip of Taub-NUT = 4D BH with D6 charge
- Black ring with BH in the middle = 2-centered 4D BH
- 17 black rings + BH = 18-centered 4D BH

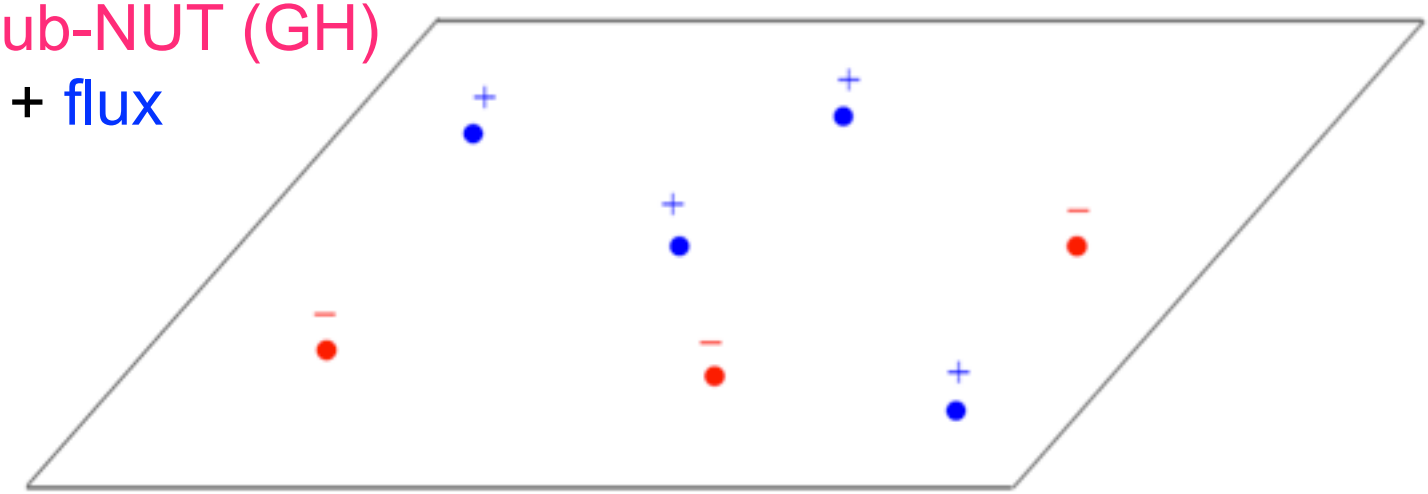
Denef



- 4D D6,D4,D2,D0 BH = 5D black hole
- 4D D4,D2,D0 BH = 5D black ring
- 5D: ring supported by angular momentum
- 4D: multicenter configuration supported by ***E x B***

Microstates geometries

Multi-center Taub-NUT (GH)
many 2-cycles + flux



Compactified to 4D → multicenter configuration Denef

- $+$ GH center $\Leftrightarrow$ $D6$ brane
- $-$ GH center $\Leftrightarrow$ $\overline{D6}$ brane

Abelian worldvolume flux
Each: 16 supercharges
4 common supercharges
(D2,D2,D2)

Lots and lots of solutions !
No singular sources or horizons
Completely smooth (@ Taub-NUT centers geometry ~ R^4)
Same mass, charge, size as BH with large horizon area

Microstates geometries

- Where is the BH charge ?

$L = q\, A_0$ magnetic

$L = \ldots + A_0\, F_{12}\, F_{34} + \ldots$

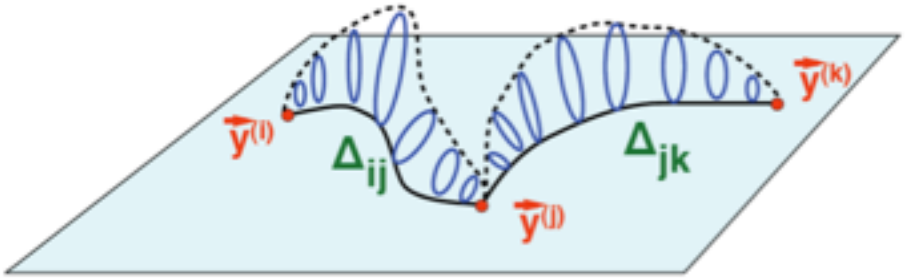
- Where is the BH mass ?

$E = \ldots + F_{12}\, F^{12} + \ldots$

- BH angular momentum

$J = E \times B = \ldots + F_{01}\, F_{12} + \ldots$

2-cycles + magnetic flux



Bubbling Geometries

Black Hole Solitons

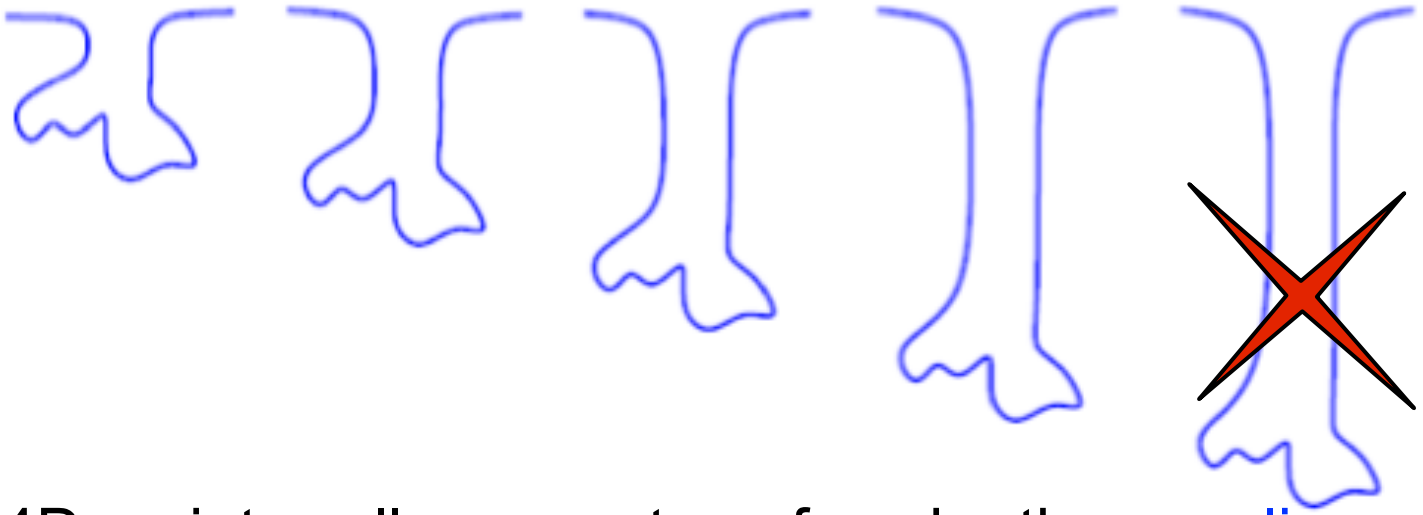
beautiful GR story behind

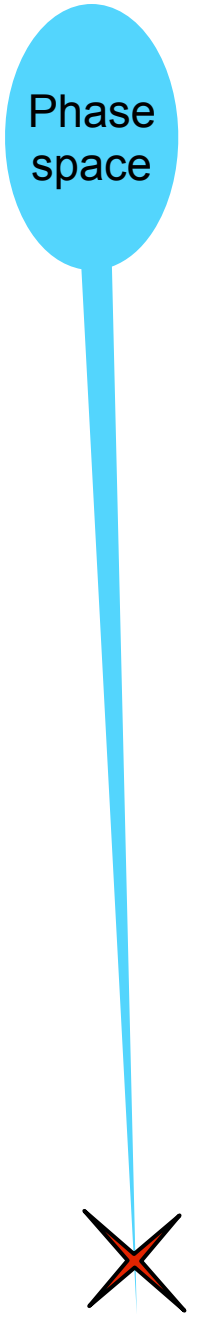
Gibbons, Warner

The charge is dissolved in magnetic fluxes. No singular sources.

Klebanov-Strassler

Deep scaling microstates



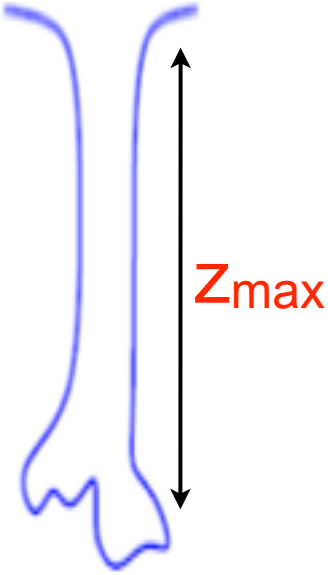


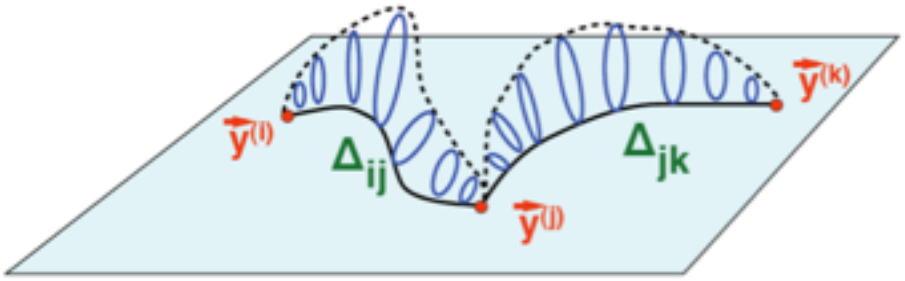
- 4D: points collapse on top of each other; scaling
- 5D: throat deeper and deeper; cap remains similar !
- Solution smooth throughout scaling !
- Long throats → small mass gap → typical CFT sector
- Scaling goes on forever !!! AdS-CFT unhappy
  - Can it be stopped ? Quantum effects ? YES
  - Destroy huge chunk of smooth horizonless solution !!!

Bena, Wang, Warner; de Boer, El Showk, Messamah, van den Bleeken

Four Scales

- Classical BH has 2 scales:
  - Mass / Horizon Size
  - Planck Length
- Microstate geometries have 2 more
  - Redshift from the bottom of the throat (scaling coefficient): z_{max}
  - Size of bubbles: $\lambda_T \sim k\,\ell_P$

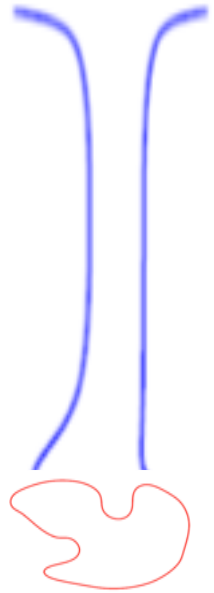




Can be traded for gap in energy spectrum E_{gap}

More general bubbling solutions

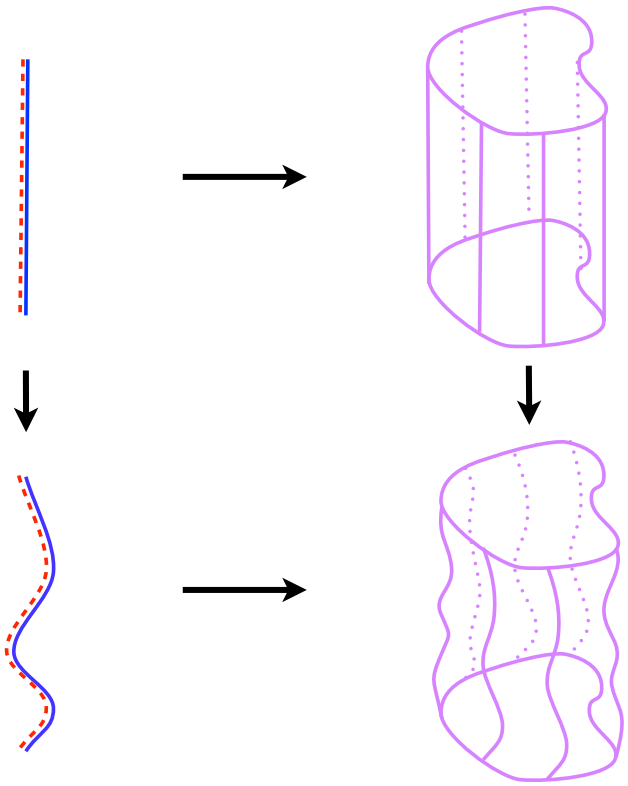
- Add supertubes (fluxed D4)
  - supersymmetric brane configs
  - arbitrary shape in 5D !!!
- Construct backreacted solution
  - Taub-NUT Green's functions (painful)
- Smooth in 6D sugra !
  - exactly as in flat space Mathur Lunin[2] Maldacena Maoz
- Entropy: $S \sim (Q^{5/2})^{1/2}$
- 5D, 6D SUGRA - evade bounds of entropy of 4D multicenter solutions
  de Boer, El Showk, Messamah, van den Bleeken
- Not yet black-hole-like ($Q^{3/2}$); getting there ☺



Even more general solutions

Bena, deBoer, Shigemori, Warner

- Supertubes (locally 16 susy) - 8 functions of one variable (c = 8)
- Superstrata (locally 16 susy) - 4 functions of two variables (c= ∞)
- Double supertube transition:



Should be Smooth !!!

Superstrata

- Want smooth solution depending on arbitrary function of 2 variables F(ψ,v)
- ψ = GH fiber, v = D1-D5 common direction
- ψ-dependent solutions — Mathur Lunin[2] Maldacena Maoz
- interchange fibers: v-dependent solutions
- more general: f(ψ) and g(v) — Niehoff, Warner

- **Superstrata entropy:**
- D1-D5 supertube: dimension of moduli space
  - classically: dimension = ∞
  - quantize: dimension = $4N_1N_5$ = number of momentum carriers
- Counting (+ fermions) — (à la Maldacena Strominger Witten)

  $S=2\pi(N_1N_5N_p)^{1/2}$!!! — Bena, Shigemori, Warner

Quiver version

- Round supertube = D4 with flux
- 5D uplift: arbitrary functions of GH fiber f(ψ)
  - Quiver 1+1dim. field theory
  - Harder to write down than QQM
  - Moduli space = functions of 1 variable !!!
- Bubble equations: average 4D charges
- 6D uplift: superstratum - F(ψ,v)
  - Quiver 2+1dim. field theory
  - Even harder
  - Moduli space = functions of 2 variables ?!?

SUSY microstates – the story:

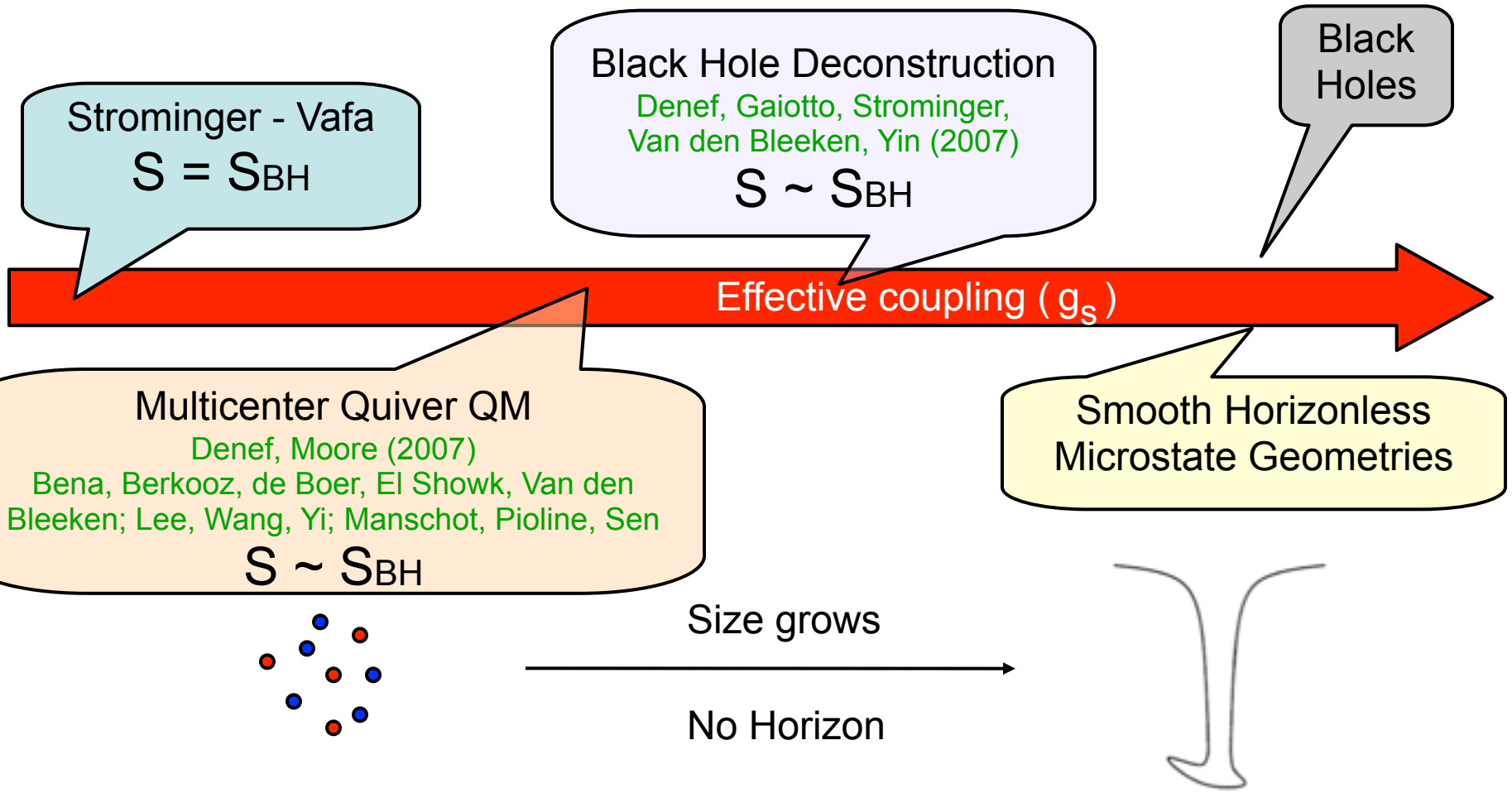
- We have a huge number of them
  - Arbitrary continuous functions
  - Smooth solutions. 4 scales !
  - Superstrata reproduce black hole entropy ☺

    Bena, Shigemori, Warner
- Dual to CFT states in typical sector
  - This is where BH states live too ☺
  - AdS-CFT: highly weird if BH microstates had horizon

    Bena, Wang, Warner; Skenderis, Taylor
- Two non-backreacted calculations:
  - BH entropy - scaling multicenter config ☺

    Denef, Moore; Denef, Gaiotto, Strominger, Van den Bleeken, Yin
  - Higgs-Coulomb map

    Bena, Berkooz, de Boer, El Showk, Van den Bleeken; Lee, Wang, Yi; Manschot, Pioline, Sen



Punchline: Typical states grow as G_N increases.

Horizon never forms.

Quantum effects from singularity extend to horizon

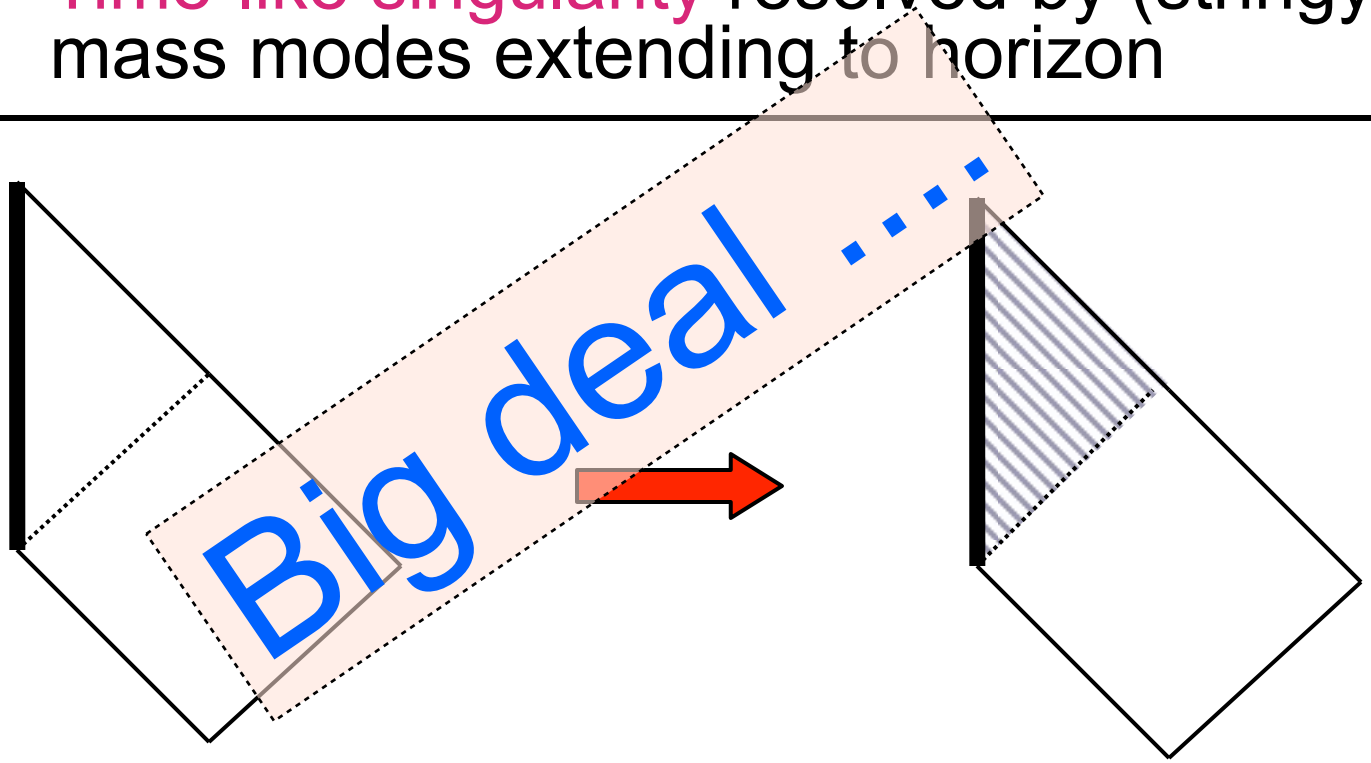
Similar story for non-SUSY extremal black holes

Why destroy horizon ? Low curvature !

- Answer: space-time has singularity:
  - low-mass degrees of freedom
  - change physics on long distances
- Very common in string theory !!!
  - Polchinski-Strassler
  - Klebanov-Strassler
  - Giant Gravitons + LLM
  - D1-D5 system
- Non-Abelian $\Leftrightarrow$ brane polarization $\Leftrightarrow$ bubbling
- Nothing holy about singularity behind horizon
  Bena, Kuperstein, Warner
- It can be even worse – QQM phase space:
  this happens even without horizon or singularity !
  Bena, Wang, Warner; de Boer, El Showk, Messamah, van den Bleeken

BPS Black Hole = Extremal

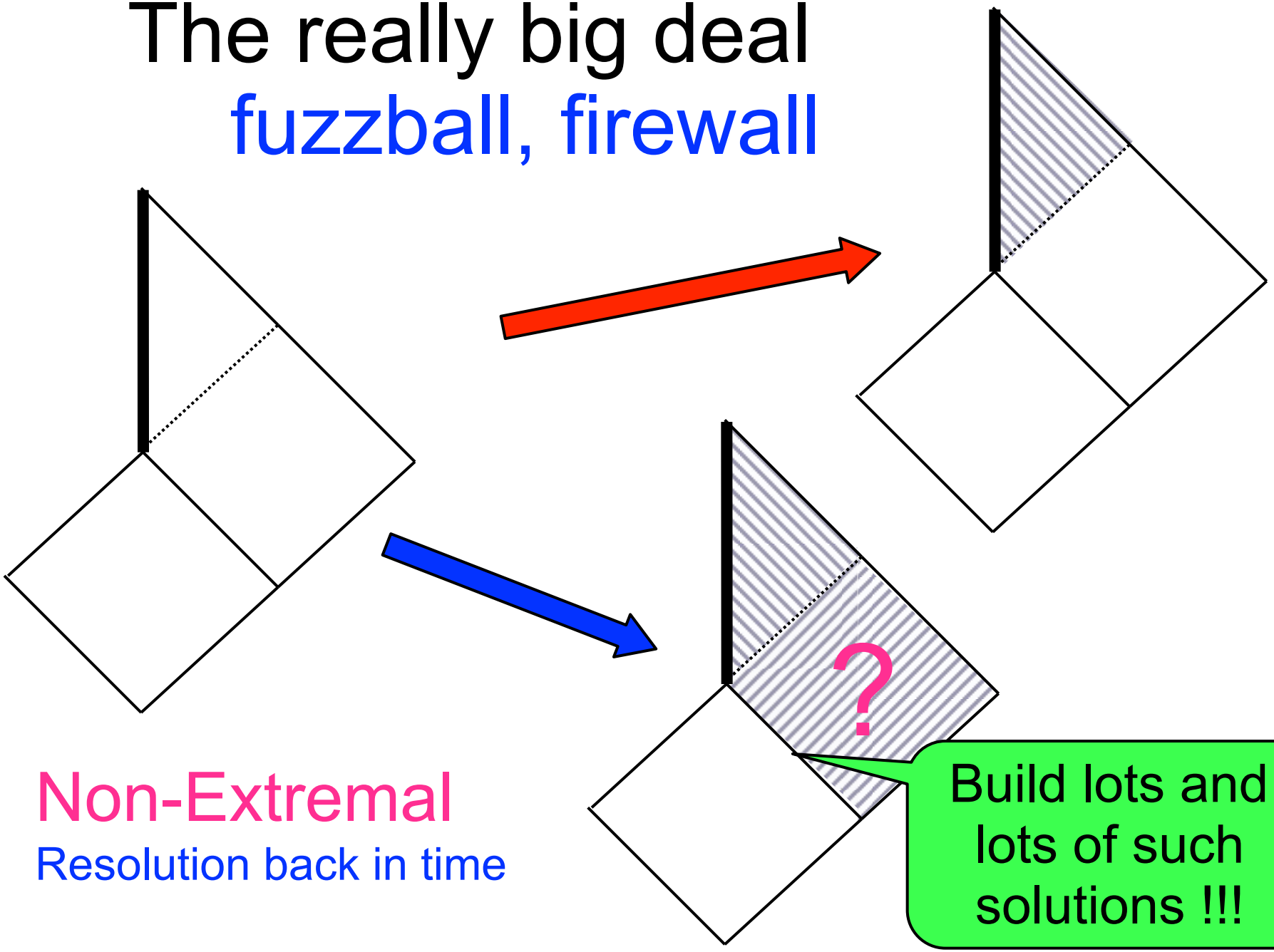
- This is not so strange
- Horizon in causal future of singularity
- Time-like singularity resolved by (stringy) low-mass modes extending to horizon



Penrose
Poisson, Israel
Dafermos
Marolf

The really big deal

fuzzball, firewall



Non-Extremal

Resolution back in time

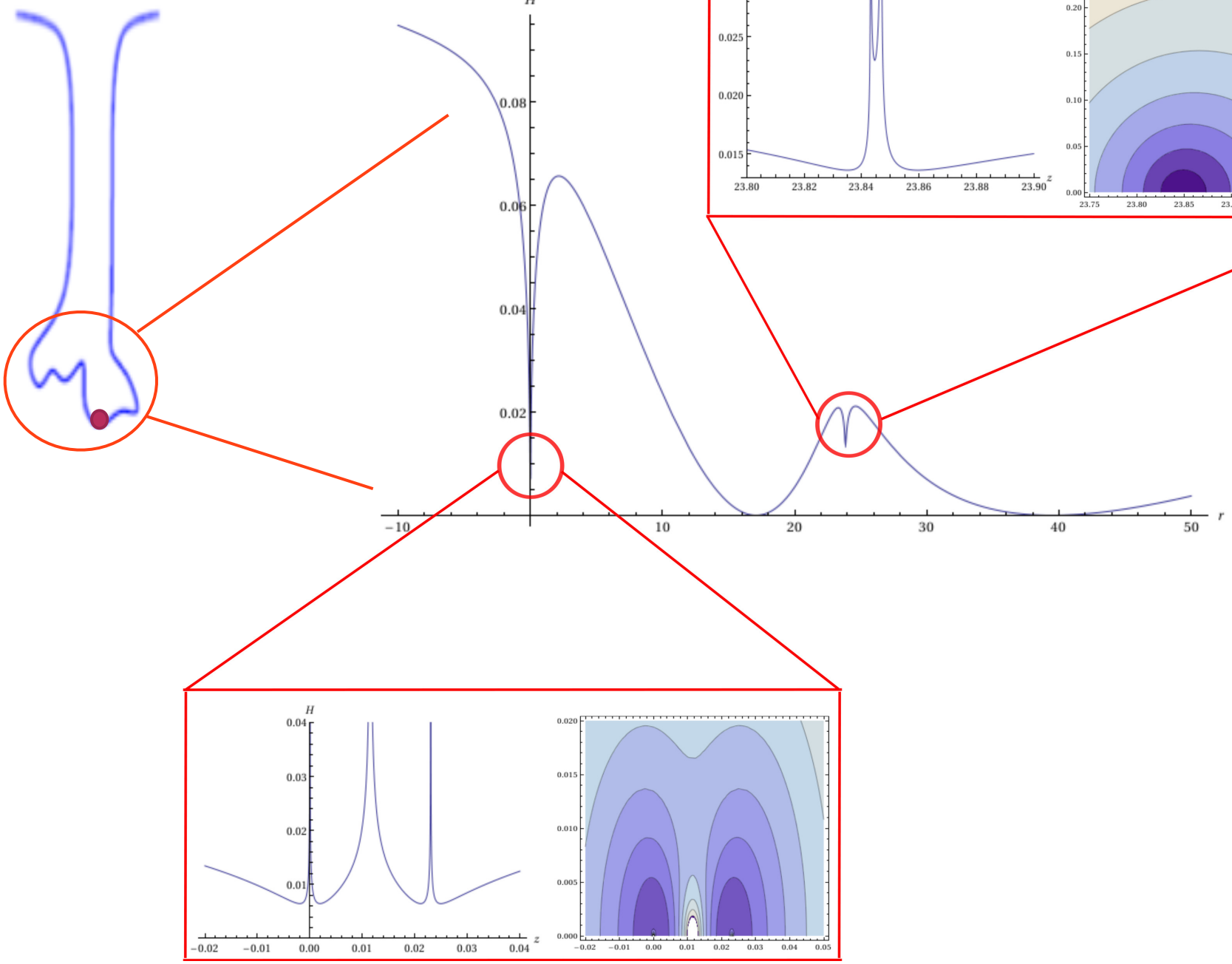
Very few known. Extremely hard to build...

– Coupled nonlinear 2‘nd order PDE’s do not factorize

Do not pray to the saint who does not help you ! Romanian proverb

- Idea: perturbative construction - near-BPS
- antibranes in backgrounds with charge dissolved in fluxes Kachru, Pearson, Verlinde
- Add supertubes to BPS bubbling sols.
- Metastable minima Bena, Puhm, Vercnocke
- Decay to susy minima:

  brane-flux annihilation - Hawking radiation
- Microstates of near-extremal BH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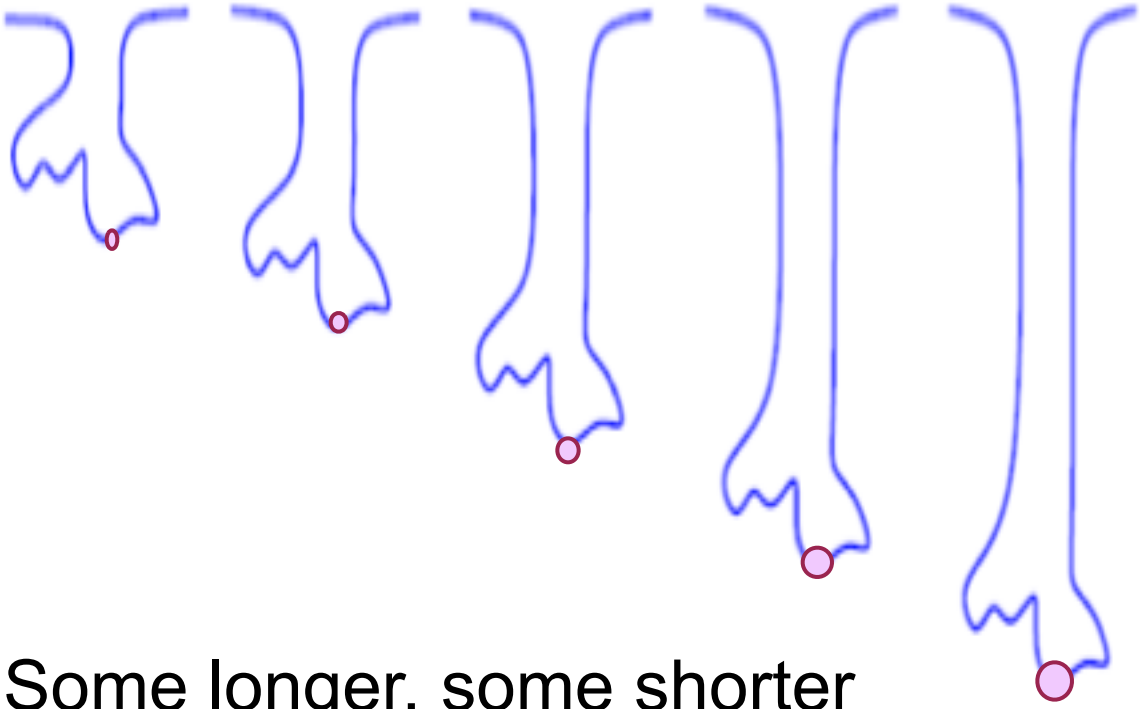
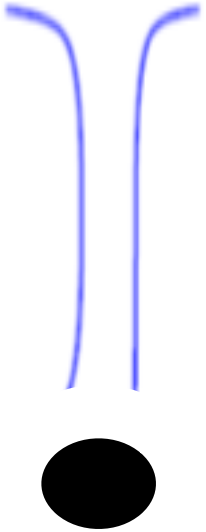
Near-Extremal BH Microstates

- Microstate geometries:



BH:

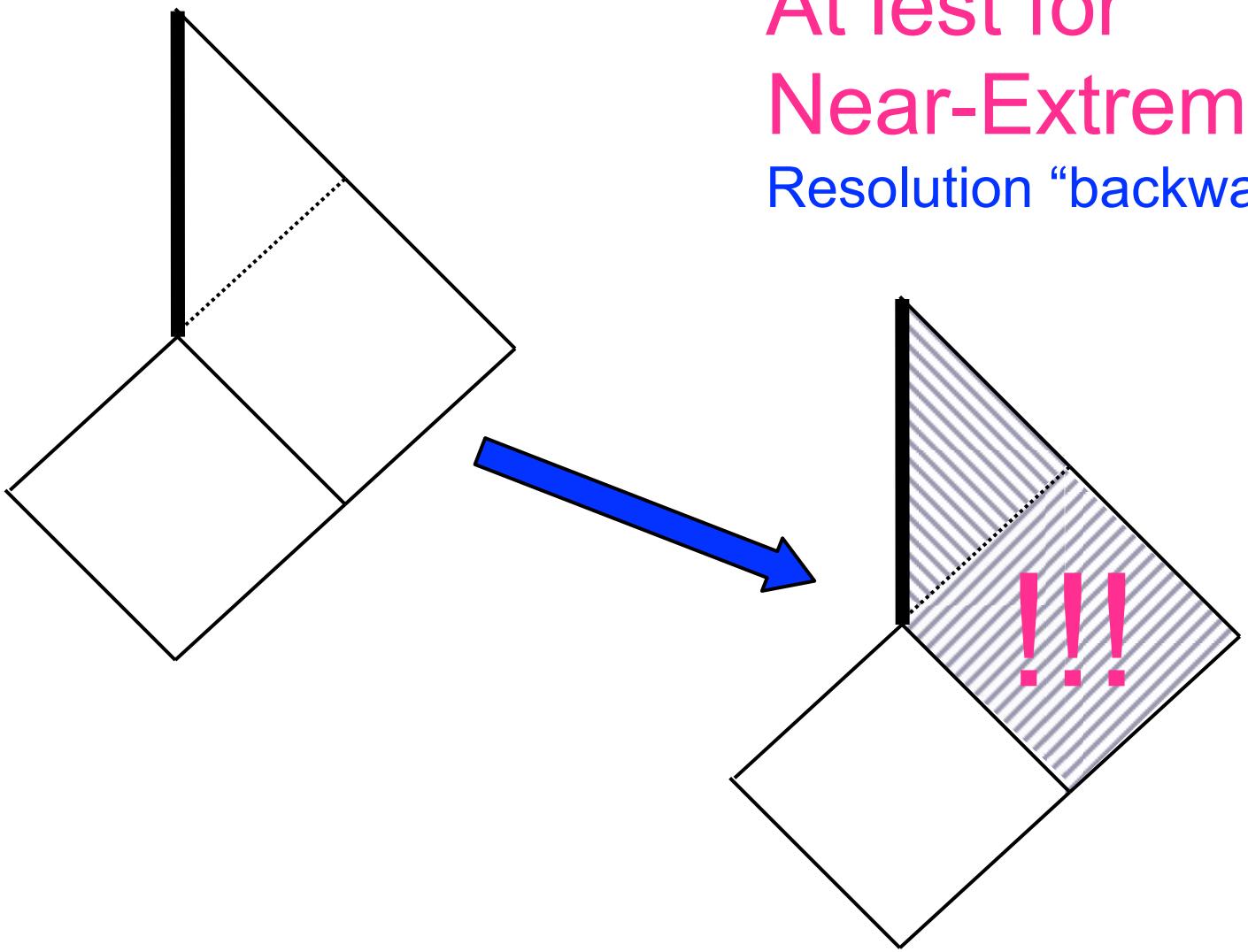


- Some longer, some shorter
- Force on branes (à la KKLMMT) wild fluctuations !!!
- Incoming observer cooked ? Definitely feel it !

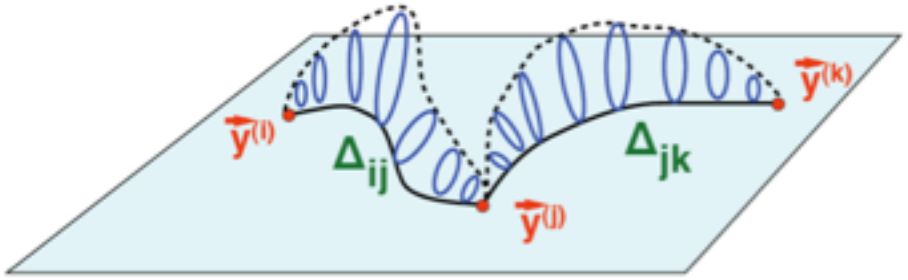
The really big deal

At lest for
Near-Extremal

Resolution “backwards in time!”

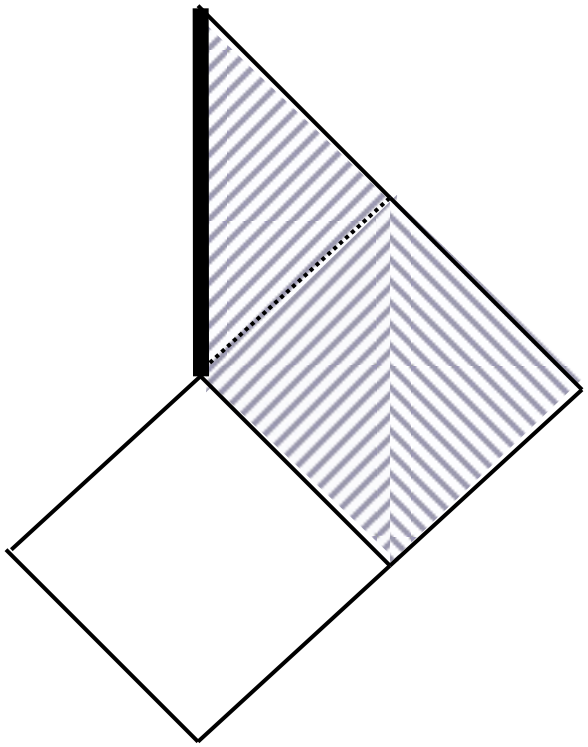


What is the mechanism ?



- Topological cycles
- Opposite fluxes
- (+) and (-) charges dissolved in fluxes.
- No Solitons without Topology Gibbons, Warner
  - Only way to build stationary solutions with BH charges
- One mechanism to hold stuff at horizon
  three hypostases:
  Bubbling (ExB) ⇔ Brane polarization ⇔ NonAbelian
- Same as physical mechanism behind wall-crossing
- Quiver version: Supergoop ? Metastable ?
  Anninos, Anous, Denef, Konstantinidis, Shaghoulian; El-Showk, Puhm, Vercnocke
- Similar to flux vacua proposal Aganagic, Beem, Seo, Vafa

What about other black holes?



- Near Extremal ?
- Schwarzschild + 1 electron ?

Take electron away

Same Penrose diagram !

String theory can resolve BH singularities

"backwards in time" Why stop at near-extremal?

Same Mechanism ?

Pure BH states have no horizon - 4 approaches:

(1) Information-theory arguments Mathur 2009, AMPS, etc
- secondary question: firewall ? burn or sail through ?

(2) Generic AdS-CFT Kkhaden, Taylor, AMPS2 (Papadodimas Raju against)
- nontrivial vevs ⇒ no spherical symmetry ⇒ no horizon

Agnostic about theory No mechanism for Hair !

(3) Follow microstates from weak to strong coupling
- BH deconstruction, Higgs-Coulomb map, String emission
  Denef, Gaiotto, Strominger, Van den Bleeken, Yin, Bena, Berkooz, de Boer, El Showk, Van den Bleeken; Lee, Wang, Yi; Manschot, Pioline, Sen, Giusto, Russo, Turton,

(4) Lots of BH microstate geometries = Hair !!!
- Mechanism: bubbles (ExB) ⇔ polarization ⇔ non-Abelian
- Universal lesson: 2 new scales, E_{gap} , λ_T
- Can account for BH entropy

A few questions

- Would all microstates be classical ?
  - No, but classical solutions are the only things we can construct
  - Hovering mechanism extrapolates ⇒ brane polarization, non-Abelian
  - Typical states: many small bubbles ($\lambda_T \sim \ell_P$), or just a few ($\lambda_T > \ell_P$)
  - Larger bubbles have more entropy Denef, Moore; Bena, Shigemori, Warner
- What about cosmological singularities ?
  - Resolved backwards in time ! How ?
  - Approaching space-like singularity - one encounters e^S new states.
  - Small tunneling probability: e^{-S}
  - Will tunnel with probability ONE !!!
- Don't people in Saclay say antibranes are bad?
- Work in progress. So far bad. Tachyonic !!!
  - BAD ⇒ no dS multiverse, near-extremal microstates = unstable
  - some people want them like this JMaRT, Mathur, Avery, Chowdhury, Turton

A few questions

- Can you fall through horizon drinking your coffee ? (as GR textbooks say)
- Do you rather go splat at the horizon scale?
- 4 options:
  - Analyze ∞ density shells / membranes / stuff carrying d.o.f. @ horizon (kept from collapsing by the Tooth Fairy)
  - Modify Gravity by weird nonlocal terms and analyze horizon
  - Modify Quantum Mechanics to keep horizon smooth at all cost
  - Use solutions and mechanisms of String Theory
- Answer likely depends on E_{gap} , λ_T
- Known bubbling solutions or polarized branes have no intention to let you fall through unharmed

Summary and Future Directions

- String theory configurations that hover above horizon.
  Topology + fluxes (ExB) ⇔ brane polarization ⇔ nonabelian d.o.f.
- BPS black hole microstates = horizonless solitons
  - low-mass modes affect large (horizon) scales
  - Convergence of many research directions
  - BPS superstrata - 2 variables - **Black Hole Entropy !**
- Extensive extremal non-BPS story
- Extend to non-extremal black holes
  - Near-extremal
    - Metastable supertubes — Bena, Puhm, Vercnocke
    - Motion on moduli space - supergoop (time-dependent) — Denef & al
  - Maybe start thinking about experimental consequences ?
  - Far from extremality ?
    - No problem in principle; so far no systematic construction
    - 2‘nd order nonlinear coupled PDE:
      - numerics? inverse scattering? blackfolds?
    - Neutral supertubes (time-dependent ?) — Mathur, Turton; Bena, Ross, Warner